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Abstract: OBJECTIVE: To determine the value of ultralow-dose chest CT for estimating the calcified atherosclerotic burden of the thoracic aorta using tin-filter CT and compare its diagnostic accuracy with chest direct radiography. METHODS: A total of 106 patients from a prospective, IRB-approved single-centre study were included and underwent standard dose chest CT (1.7 ± 0.7 mSv) by clinical indication followed by ultralow-dose CT with 100 kV and spectral shaping by a tin filter (0.13 ± 0.01 mSv) to achieve chest X-ray equivalent dose in the same session. Two independent radiologists reviewed the CT images, rated image quality and estimated presence and extent of calcification of aortic valve, ascending aorta and aortic arch. Conventional radiographs were also reviewed for presence of aortic calcifications. RESULTS: The sensitivity of ultralow-dose CT for the detection of calcifications of the aortic valve, ascending aorta and aortic arch was 93.5, 96.2 and 96.2%, respectively, compared with standard dose CT. The sensitivity for the detection of thoracic aortic calcification was significantly lower on chest X-ray (52.3%) compared with ultralow-dose CT ($p < 0.001$). CONCLUSION: A reliable estimation of calcified atherosclerotic burden of the thoracic aorta can be achieved with modern tin-filter CT at dose values comparable to chest direct radiography. Advances in knowledge: Our findings suggest that ultralow-dose CT is an excellent tool for assessing the calcified atherosclerotic burden of the thoracic aorta with higher diagnostic accuracy than conventional chest radiography and importantly without the additional cost of increased radiation dose.

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FULL PAPER

Diagnostic accuracy of chest X-ray dose-equivalent CT for assessing calcified atherosclerotic burden of the thoracic aorta

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Objective: To determine the value of ultralow-dose chest CT for estimating the calcified atherosclerotic burden of the thoracic aorta using tin-filter CT and compare its diagnostic accuracy with chest direct radiography.
Methods: A total of 106 patients from a prospective, IRB-approved single-centre study were included and underwent standard dose chest CT (1.7 ± 0.7 mSv) by clinical indication followed by ultralow-dose CT with 100 kV and spectral shaping by a tin filter (0.13 ± 0.01 mSv) to achieve chest X-ray equivalent dose in the same session. Two independent radiologists reviewed the CT images, rated image quality and estimated presence and extent of calcification of aortic valve, ascending aorta and aortic arch. Conventional radiographs were also reviewed for presence of aortic calcifications.
Results: The sensitivity of ultralow-dose CT for the detection of calcifications of the aortic valve, ascending aorta and aortic arch was 93.5, 96.2 and 96.2%, respectively, compared with standard dose CT. The sensitivity for the detection of thoracic aortic calcification was significantly lower on chest X-ray (52.3%) compared with ultralow-dose CT ($p < 0.001$).
Conclusion: A reliable estimation of calcified atherosclerotic burden of the thoracic aorta can be achieved with modern tin-filter CT at dose values comparable to chest direct radiography.
Advances in knowledge: Our findings suggest that ultralow-dose CT is an excellent tool for assessing the calcified atherosclerotic burden of the thoracic aorta with higher diagnostic accuracy than conventional chest radiography and importantly without the additional cost of increased radiation dose.

INTRODUCTION

Stroke is a severe complication of patients undergoing cardiac surgery with an incidence rate of 1.4–9.7%.[1] Post-operative stroke is associated with high mortality and longer period of hospitalization.[2] Unfortunately, its frequency has not decreased during the past 10 years.[3] The incidence of stroke is strongly related to the performed surgical procedure.[4,5] The majority of post-operative strokes are embolic in nature and caused by mobilization of atherosclerotic material of the aortic wall during the operation.[5,6] It is estimated that patients with calcification of the ascending aorta have a five-fold higher risk for developing post-operative stroke.[7] Intraoperative manual palpation of the aortic arch has only modest accuracy for detection of atheroma within the thoracic aorta[8] and intraoperative ultrasound has its limitation owing to narrow anatomical coverage and operator dependency.[9]

Thoracic aortic calcification can be reliably quantified on CT[10] and several small studies have reported that preoperative CT in cardiac surgery may reduce postoperative stroke rate by altering surgical strategy and avoiding heavy manipulation of the aorta.[11] However, CT goes along with potentially harmful effects of radiation exposure.[12]

Recent technical innovations allowed to lower the radiation exposure received from chest CT to levels similar to digital radiography.[13] Such ultralow-dose CT applications have so far only been validated for lung nodule detection and emphysema quantification.[14–18] We, therefore, sought

Table 1. Patient demographics and indications for CT of study patients (n = 106)

Characteristics	
Female/male	43 (41%)/63 (59%)
Age (years)	62 ± 14 (19–89)
Weight (kg)	75 ± 18 (40–132)
Height (m)	1.68 ± 0.1 (1.47–1.92)
BMI (kg m^{-2})	26.4 ± 5.7 (16.2–49.0)
Clinical indication for CT	
Known or suspected tumour	55 (52%)
Suspected pulmonary infection	4 (4%)
Work-up or follow-up of pulmonary nodule	10 (9%)
Work-up or follow-up of pulmonary disease	23 (22%)
Abnormal chest X-ray findings	5 (5%)
Vascular[a]	7 (7%)
Skeleton assessment[b]	2 (2%)

BMI, body mass index; presented as n (%) and mean ± SD (range).
[a]*e.g.* prior to transcatheter aortic valve implantation.
[b]*e.g.* prior to surgical treatment of pectus excavatum.

to determine the value of ultralow-dose chest CT for estimation of the calcified atherosclerotic burden of the thoracic aorta and compare its diagnostic accuracy with conventional chest radiography.

METHODS AND MATERIALS

Study population

Our local ethics committee approved this prospective single-centre study (clinicaltrials.gov identifier NCT0246860). All patients provided written informed consent prior to inclusion. Part of the study group and a detailed description of inclusion/exclusion criteria are reported in a previous publication.[16] For the present study, all patients undergoing unenhanced CT (n = 50) for clinical indication were included. Further, an additional total of 56 patients were randomly selected using a random number generator (http://stattrek.com/Tables/Random.aspx). The total study population included 63 male, 43 female; mean age 62 years; range 19–89 years. Patient demographics are depicted in Table 1.

CT acquisition and radiation dose

Each patient underwent two CT scans of the chest in a single session at two different dose levels. All scans were conducted with a third-generation dual-source CT (Somatom Force, Siemens Healthcare, Forchheim, Germany). A collimation of 96 × 0.6 mm was obtained with a slice acquisition of 192 × 0.6 mm by means of a z-flying focal spot. The gantry rotation-time was 0.5 s with a pitch of 1.2, and all scans were acquired in full inspiratory breath hold. Patients were scanned with our clinical standard chest CT protocol, followed by the ultralow-dose scan with the same scan length and the same starting position. First, standard-dose scans were obtained with reference settings of 110 kV and 50 quality reference mAs using automated attenuation-based tube potential selection (CAREkV; Siemens Healthcare, Forchheim, Germany; setting 7) and automated attenuation-based tube current modulation (CAREDose4D; Siemens Healthcare, Forchheim, Germany). Secondly, ultralow-dose CT scans were performed at a fixed tube potential of 100 kV and a fixed tube current-time product of 70 mAs with tin-filtration of the X-ray spectrum, resulting in a $CTDI_{vol}$ of 0.24 mGy.

CT dose index and dose-length product of each scan were automatically recorded. The effective dose was calculated by multiplying the dose-length product with a conversion factor of 0.014 mSv/mGy cm.[19] Radiation dose parameters of the study protocols are presented in Table 2.

Image reconstruction and assessment

All images were reconstructed with advanced modelled iterative reconstruction at a strength level of three, from a total five incremental strength levels, where Level 1 has the lowest and Level 5 has the highest degree of noise reduction.[20] A slice thickness of 2 mm and an increment of 1.6 mm using a smooth tissue convolution kernel (Br40) were used. Images were reviewed on a high-definition liquid crystal display monitor (BARCO; Medical Imaging Systems, Kortrijk, Belgium) using the picture archiving and communication system (ImpaxEE, v. R20XVSU2; Agfa Healthcare NV, Belgium) of Division of Radiology and Nuclear Medicine, Cantonal Hospital St. Gallen, Switzerland. The two radiologists involved in the image analysis were free to use all the capabilities of the picture archiving and communication system at their own discretion (*e.g.* multiplanar reformations).

Table 2. Radiation dose parameters of study protocols

Parameter	Standard-dose CT	Ultralow-dose CT	p-value[a]
$CTDI_{vol}$ (mGy)	3.2 ± 1.2 (1.1–8.2)	0.24[b]	<0.001
Scan length (cm)	33.8 ± 3.0 (27.9–42.1)	33.8 ± 3.0 (27.9–42.1)	1.000
DLP (mGy cm)	124.3 ± 47.8 (45.9–295.3)	9.3 ± 0.7 (7.9–11.2)	<0.001
ED (mSv)	1.7 ± 0.7 (0.6–4.1)	0.13 ± 0.01 (0.11–0.16)	<0.001

$CTDI_{vol}$, volume CT dose index; DLP, dose length product; ED, effective dose, presented as mean ± SD (range).
[a]Wilcoxon-test for paired non-parametric data.
[b]Fixed tube potential and fixed tube current-time product.

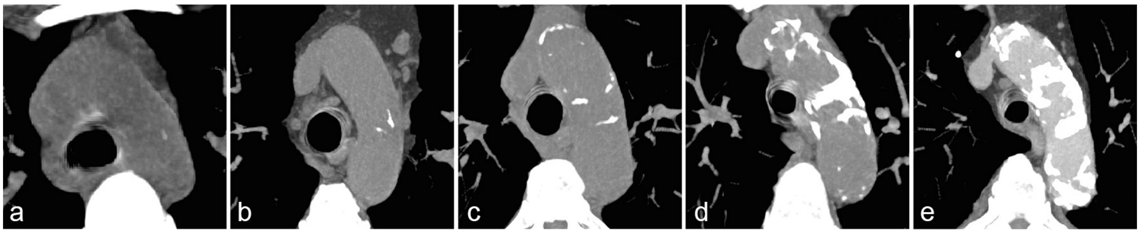


Figure 2. Representative examples of each level of calcium quantity for the aortic arch give an impression on how the readers assessed the images, with categories of no/absent (a), minimal (b), mild (c), moderate (d) and severe (e) calcifications.

Qualitative image analysis

Each scan was rated on a 5-point Likert scale with regard to the diagnostic value for calcifications, as previously suggested[21]: 1 for poor quality, no distinction can be made between noise and (small) calcifications, limited diagnostic value; 2 for insufficient quality, little distinction can be made between noise and (small) calcifications, limited diagnostic value; 3 for moderate quality, small chance of missing small calcifications, just diagnostic; 4 for proper quality, unlikely that calcifications are missed, good diagnostic value; and 5 for excellent quality, certainly no calcifications are missed, excellent diagnostic value. Scans with a rating of 1 or 2 were considered as non-diagnostic. In an intent-to-diagnose approach, all data sets were included into diagnostic accuracy analysis, even if the image quality was considered non-diagnostic. The subjective rating was performed by two independent blinded radiologists and in case of ratings discrepancy a decision was made by consensus.

Visual estimation of thoracic aortic atherosclerotic burden

All data sets were reviewed by two radiologists (MM and RWB, with 4 and 9 years of experience in radiology) in three separate reading sessions. Each reading session was performed with a 4-week interval to minimize the risk for recall bias. Images were reviewed in random order and readers were blinded to any clinical information. In case of discrepancy of grading, a final decision was made by consensus including a third radiologist.

In a first reading session, radiologists reviewed standard-dose CT images. Radiologists estimated the presence and extent of calcification of (a) the aortic valve, (b) the ascending aorta and (c) the aortic arch. The extent of calcification for each localization was categorized as being absent, minimal, mild, moderate or severe, respectively. Examples of each level of calcium load for aortic valve and arch is given in Figures 1 and 2.

In a second reading session, radiologists reviewed ultralow-dose CT images. Radiologists estimated the presence and extent of calcification in the same fashion as for standard-dose CT.

In a third reading session, radiologists reviewed posteroanterior and lateral view chest X-rays. The chest X-rays were only included if they were performed within 3 months from the time the study CT was conducted and if both views were available (n = 49, *i.e.* 46% of study group). If no chest X-ray of the patient was available at all in this time period (n = 57, *i.e.* 54% of study group), an X-ray mimic was created by creating a thick multiplanar reformation in posteroanterior and lateral projection from the CT data set of the ultralow-dose scan by a third radiologist. The presence and extent of calcification of the thoracic aorta in chest X-ray was estimated and categorized as absent, moderate or severe, respectively.

STATISTICAL ANALYSIS

Continuous data were expressed as mean ± SD. Wilcoxon- and χ^2 test were used to compare paired and unpaired non-parametric data, respectively. Sensitivity and specificity for calcium detection of the ascending aorta and arch per patient was calculated for chest X-ray using standard-dose CT as standard of reference. Sensitivity and specificity for calcium detection for (a) the aortic valve, (b) the ascending aorta and (c) the aortic arch was calculated for ultralow-dose CT using standard-dose CT as standard of reference. Further, agreement of calcium quantity between standard-dose and ultralow-dose images in the aortic valve, ascending aorta and aortic arch was determined using quadratic weighted kappa statistics, with 95% CIs. The κ-values were interpreted as: poor ($\kappa < 0.20$), fair ($\kappa = 0.21–0.40$), moderate ($\kappa = 0.41–0.60$), good ($\kappa = 0.61–0.80$) and excellent ($\kappa = 0.81–1.00$) agreement. SPSS 23.0 (IBM Corporation, Armonk, NY) and MedCalc v. 13.2.2.0 (MedCalc Software, Ostend, Belgium) were used for statistical analyses. A two-sided p-value < 0.05 was considered statistically significant.

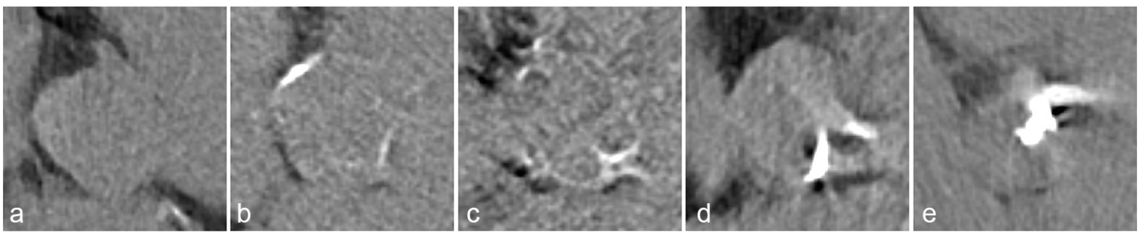


Figure 1. Representative examples of each level of calcium quantity for the aortic valve give an impression on how the readers assessed the images, with categories of no/absent (a), minimal (b), mild (c), moderate (d) and severe (e) calcifications.

Table 3. Subjective image quality with regard to the diagnostic value for estimation of the atherosclerotic burden of the thoracic aorta in standard and ultralow-dose CT

Parameter	Standard-dose CT	Ultralow-dose CT	p-value[a]
Mean image quality	4.9	3.9	<0.001
Image quality ratings[b]			<0.001
Grade 5	103 (97%)	9 (8%)	
Grade 4	2 (2%)	79 (75%)	
Grade 3	1 (1%)	17 (16%)	
Grade 2[c]	0 (0%)	1 (1%)	
Grade 1[c]	0 (0%)	0 (0%)	

Data are presented as mean or *n* (%).
[a]Wilcoxon-test for paired non-parametric data and χ^2 test for non-paired non-parametric data.
[b]Included are the ratings by consensus of three radiologists.
[c]Indicating a non-diagnostic scan.

RESULTS

The images of 106 patients were assessed, including standard-dose CT, ultralow-dose CT and chest X-rays yielding a total of 318 data sets.

Qualitative image results

The subjective image quality with regards to the diagnostic value for aortic calcification was rated lower for ultralow-dose CT images with a mean of 3.9 as compared with standard-dose images with a mean of 4.9, ($p < 0.001$) (Table 3). In total, only one case (1%) was rated as non-diagnostic for aortic calcium detection on ultralow dose CT.

Diagnostic accuracy of chest X-ray and ultralow-dose CT for the detection of thoracic aortic calcifications

The diagnostic accuracy for the detection of thoracic aortic calcification was significantly lower on chest X-ray compared with ultralow-dose CT ($p < 0.001$) (Table 4). The combined sensitivity for the detection of calcifications of the ascending aorta and aortic arch was 52.5% for chest X-ray. The sensitivity for the detection of calcifications of the ascending aorta and aortic arch was 93.5, 96.2 and 96.2%, respectively in ultralow-dose CT.

Value of ultralow-dose CT for estimation of aortic valve, ascending aorta and aortic arch calcifications

There was a high agreement for calcium quantity estimation between standard-dose and ultralow-dose images with weighted κ-values of 0.966, 0.973 and 0.972, in the aortic valve, ascending aorta and aortic arch, respectively ($p$all <0.001) (Table 5). Representative cases of standard-dose, ultralow-dose CT and plain chest X-ray are depicted in Figures 3 and 4.

DISCUSSION

The present study sought to determine the diagnostic value of ultralow-dose chest CT for the estimation of the calcified atherosclerotic burden of the thoracic aorta and compare its accuracy with conventional chest radiography.

Table 4. Diagnostic performance of plain chest X-ray and ultralow-dose CT for the detection of thoracic aortic calcifications with standard-dose CT as reference

Parameter	Chest X-ray	Ultralow-dose CT			p-value[a]
	Aorta	Aortic valve	Ascending aorta	Aortic arch	
Sensitivity	52.5% (41.0–63.8)	93.5% (78.6–99.2)	96.2% (87.0–99.5)	96.2% (89.3–99.2)	<0.001
Specificity	69.2% (48.2–85.7)	97.3% (90.7–99.7)	100.0% (93.3–100.0)	92.6% (75.7–99.1)	
PPV	84.0% (70.9–92.8)	93.6% (78.6–99.2)	100.0% (93.3–100.0)	97.4% (91.0–99.7)	
NPV	32.1% (20.3–46.0)	97.3% (90.7–99.7)	96.4% (87.5–99.6)	89.3% (71.8–97.7)	
True-positive (*n*)	42	29	51	76	
False-negative, (*n*)	38	2	2	3	
False-positive (*n*)	8	2	0	2	
True-negative (*n*)	18	73	53	25	

NPV, negative predictive value; PPV, positive predictive value.
Data are presented as sensitivity, specificity, PPV, NPV % (95% CI).
[a]Pairwise comparison of sensitivity of chest X-ray and ultralow-dose CT using χ^2 test.

Table 5. Agreement of chest X-ray and ultralow-dose with standard-dose CT regarding extent of thoracic atherosclerotic burden

	Standard-dose CT				
Chest X-ray	**Aorta**				
	Absent	Minimal	Mild	Moderate	Severe
Absent	18	31	7	0	0
Moderate	8	11	14	9	0
Severe	0	0	3	4	1
	Aortic valve				
Ultralow-dose CT	Absent	Minimal	Mild	Moderate	Severe
Absent	73	2	0	0	0
Minimal	2	20	1	0	0
Mild	0	0	2	0	0
Moderate	0	0	0	5	0
Severe	0	0	0	0	1
	Ascending aorta				
	Absent	Minimal	Mild	Moderate	Severe
Absent	53	2	0	0	0
Minimal	0	35	0	0	0
Mild	0	1	15	0	0
Moderate	0	0	0	0	0
Severe	0	0	0	0	0
	Aortic arch				
	Absent	Minimal	Mild	Moderate	Severe
Absent	25	3	0	0	0
Minimal	2	39	0	0	0
Mild	0	0	22	0	0
Moderate	0	0	1	13	0
Severe	0	0	0	0	1

Stroke after cardiac surgery is a feared complication with still relatively high incidence[1] and recent studies have reported that pre-operative visualization of the thoracic aorta by CT may reduce stroke risk.[11] Several studies found a decrease in post-operative stroke rates from 3.0 to 0.7%[22] and from 9.0 to 0.4%,[23] respectively of patients undergoing pre-operative CT compared with a control group without pre-operative imaging. The investigators reported a change in surgical approach mainly with respect to different cannulation site selection and the use of an off-pump no-touch operation technique.[22,23] Currently, pre-operative CT is not routinely performed prior to cardiac surgery also owing to relatively high radiation exposure of CT with the potential risk of radiation-induced malignancy. Standard pre-operative work-up before cardiac surgery includes evaluation by chest X-ray, however, it was reported that plain X-ray only detects large calcified areas and generally underestimates thoracic aortic atherosclerosis.[24] This was also observed in our study where the sensitivity of X-ray for detecting thoracic aorta calcification was only 52.2%. In contrast, ultralow-dose CT showed a statistically significantly higher sensitivity for the detection of aortic calcification (93.5–96.2%). Moreover, ultralow-dose CT allowed for anatomically differentiated assessment, with a high agreement of calcium quantity estimation of the aortic valve, ascending aorta and aortic arch as compared with standard-dose CT. An accurate preoperative visualization of the extent and location of aortic calcifications is important if it is needed for preoperative planning and adaptation of the strategy for cardiac surgery.[25]

Regarding radiation dose, the mean effective dose of ultralow-dose CT in this study was 0.13 mSv and is, thereby, similar to chest radiography, which are on average 0.1 mSv for a posteroanterior and lateral study.[13]

The clinical utility of low-dose CT prior to cardiac CT is currently being further evaluated by the ongoing CRICKET study which investigates whether pre-operative knowledge regarding the location and extent of aortic calcifications can be used to optimize surgical strategy and, thereby, decrease post-operative stroke rate.[26] In the CRICKET study, dose levels of below 1 mSv are used for CT.[27]

Figure 3. Representative posteroanterior chest X-ray image (a) as well as transverse CT sections scanned with standard-dose CT (b, d, e) (effective dose 1.57 mSv) and ultralow-dose CT (c, f, g) (effective dose 0.12 mSv) in a 83-year-old female with a BMI of 26.1 kg m^{-2}. As the images illustrates ultralow-dose CT allowes for anatomically differentiated assessment, with a high agreement of calcium quantity estimation of the aortic valve, ascending aorta and aortic arch as compared with standard-dose CT.

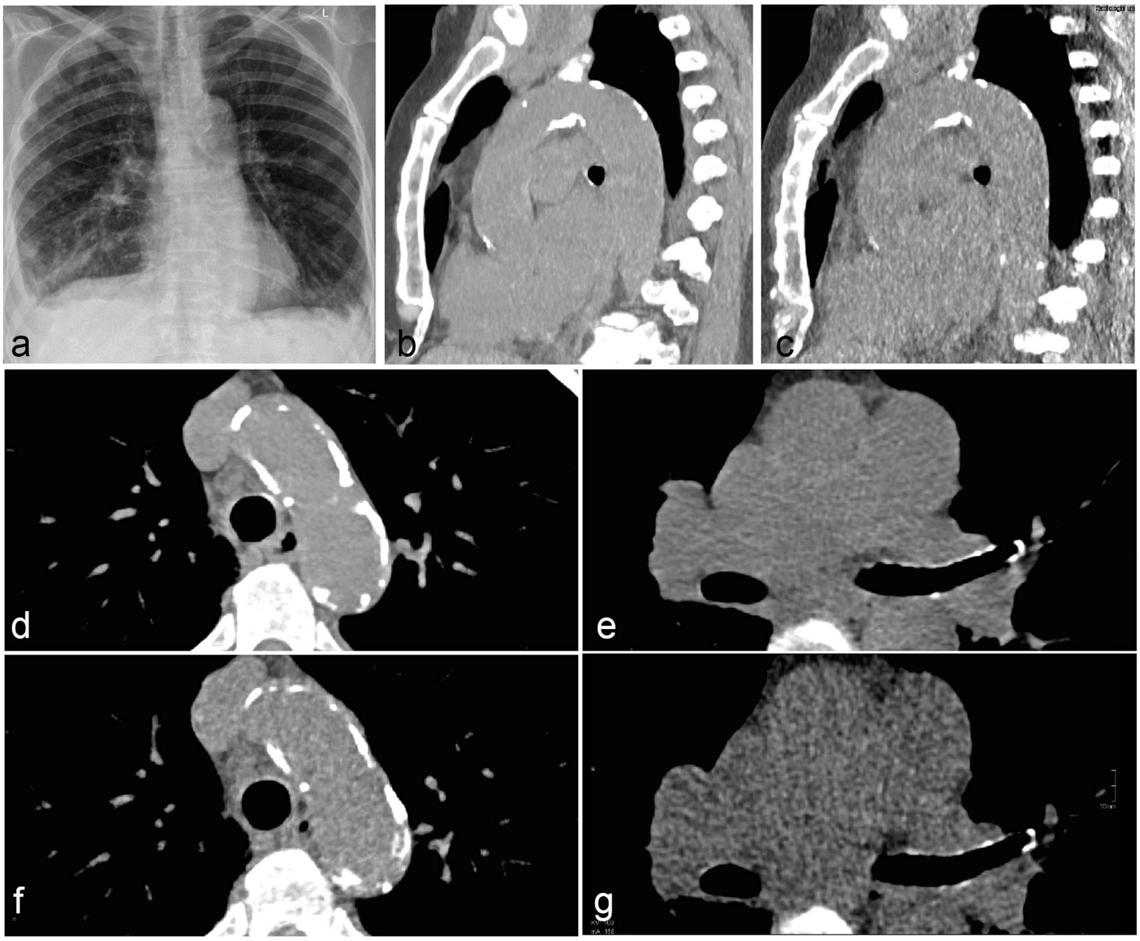
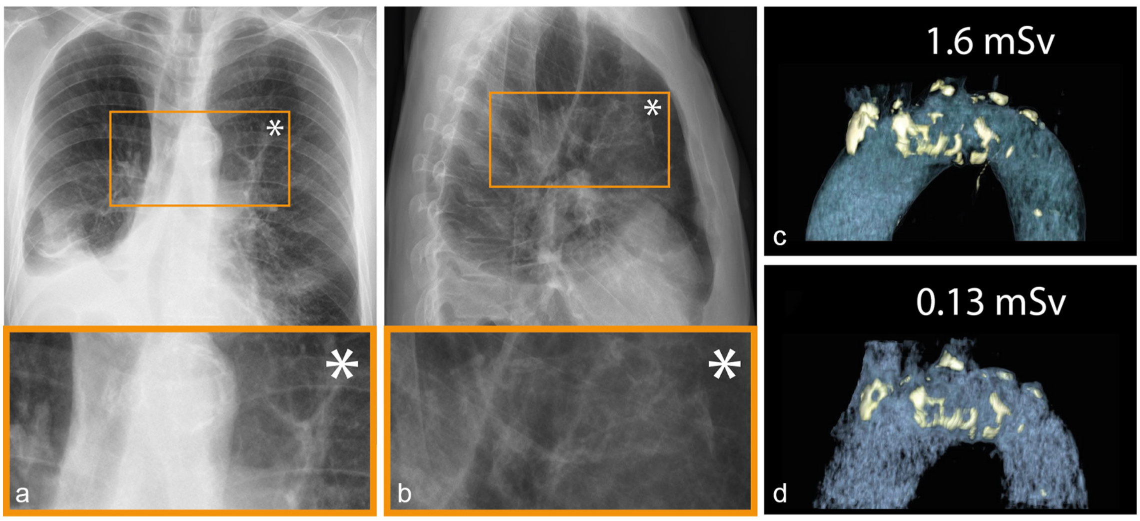


Figure 4. Representative posteroanterior (a) and lateral (b) chest X-rays of a 63-year-old male with a body mass index of 21.8 kg m^{-2}. Some calcifications of the aortic arch (asterisk; zoomed images) can be seen in both views of X-ray images, however 3D volume rendering images based on standard-dose CT (c) (effective dose 1.62 mSv) and ultralow-dose CT (d) (effective dose 0.13 mSv) allow for a more detailed estimation of the amount and localization of aortic calcifications.



Previous studies already reported that the dose for aortic calcification detection can be substantially lowered to 0.4–0.5 mSv.[21,27] However, our study is the first to show that a chest X-ray equivalent dose level allows for a reliable estimation of calcified atherosclerotic burden. In general, low dose levels similar to those from plain X-ray are desired when it is intended to replace chest X-ray with CT for a certain diagnostic purpose. In case of a positive result from the CRICKET trial, our study may be one piece of evidence showing that novel ultralow-dose techniques are a valid tool for assessing the atherosclerotic burden of the thoracic aorta with higher diagnostic accuracy than conventional chest radiography but without the additional cost of increased radiation dose. As we benefit from the advantages of a cross-sectional imaging modality that allows for an anatomically differentiated assessment this will be a major argument against parties expressing their reservation.

Our study has some limitations to be considered. The first limitation is the limited number of patients. In addition, it may be perceived as a limitation that we did not include patients with extensive atherosclerosis. However, we have observed a high agreement of calcification estimation in different localization even in patients with only minimal to moderate atherosclerosis. Thus, we believe that we still can appraise the diagnostic value of the tested technique. Further studies including patients prior to cardiac surgery like the CRICKET study may elucidate the value of ultralow-dose CT in a target study group and diagnostic setting.

In conclusion, a reliable estimation of calcified atherosclerotic burden of the thoracic aorta can be achieved with ultralow-dose CT using a third-generation dual-source scanner with tin filter technology. Further, the diagnostic accuracy of ultralow-dose is significantly higher than chest radiography.

CONFLICT OF INTEREST

Prof. Dr Ralf Bauer is on the speakers' bureau of Siemens Healthcare. Otherwise we disclose no financial support or author involvement with organizations with financial interest in the subject matter. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

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